Lower Cretaceous reservoir development in the North Sea Central Graben and potential analogue settings in the Southern Permian Basin and South Viking Graben

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ABSTRACT

Much of the future hydrocarbon exploration potential in the North Sea lies in locating stratigraphic traps and discrete reservoir intervals. This study assesses the potential for Lower Cretaceous reservoirs, with particular focus on the Norwegian Central Graben and proposed methods to identify future prospects over a wider area. Seismic interpretation and well data reveal the structure and sedimentology of the study area. Although the region was isolated from a large hinterland in the Early Cretaceous, potential local sediment sources, sediment transport routes and areas with possible reservoir development are identified. The greater Mandal High area, where Lower Cretaceous shoreface deposits and submarine fan systems are postulated, is suggested for primary focus. Similar deposits may have developed around the other exposed highs in the region, although several were drowned towards the end of the Early Cretaceous. Detailed seismic and stratigraphic analysis will be necessary to identify individual reservoir units. Since similar settings may have occurred in the adjacent South Viking Graben and Southern Permian Basin regions during the Early Cretaceous, further reservoir assessment is recommended for the North Sea in general.

KEYWORDS: Lower Cretaceous, Tectonics, Reservoir prediction, Hydrocarbon exploration

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The Central Graben of the North Sea represents a prolific and mature hydrocarbon province (e.g. Brooks 1990). Despite 50 years of exploration, further potential continues to be unlocked as demonstrated by the Upper Jurassic shoreface play (e.g. Edvard Grieg and Johan Sverdrup discoveries at the Norwegian Utsira High, Jørstad 2012; NPD 2017; Lundin 2017) and by the Upper Jurassic turbidite play in the United Kingdom (UK) Moray Firth (e.g. Buzzard field, Fraser *et al*. 2003; Ray *et al*. 2010). This paper describes further potential in another stratigraphic horizon, namely the Lower Cretaceous reservoirs of the North Sea. Here shoreface and deep water reservoir units are developed associated with discrete Mesozoic rifting phases and related localised depocenters.

Lower Cretaceous deep marine sandstones represent an important play in the UK Moray Firth (e.g. Garrett *et al*. 2000; Johnson *et al*. 2005, Figs. 1a, 2), where large amounts of sand from the exposed East Orkney High and Halibut Horst were shed into adjacent basins of the Inner- and Outer Moray Firth, forming the reservoirs for various hydrocarbon fields (e.g. Scapa, Britannia, McGann *et al*. 1991; Ainsworth *et al*. 2000). Various studies have established sediment transport directions (Hailwood & Ding 2000), sediment provenance areas (Blackbourn & Thomson 2000) and a sequence stratigraphic framework (Jeremiah 2000) in this area.

In contrast to the Moray Firth, the Lower Cretaceous play remains underdeveloped in the Central Graben (Copestake *et al*. 2003; NPD 2017). While the generalised Mesozoic sequence is visible on seismic in the Moray Firth, the thick (2000 to 4500 m) Cenozoic and Upper Cretaceous overburden in the Central Graben presents an issue for seismically driven reservoir identification within the Lower Cretaceous (up to 30 m net reservoir thickness) (Argent *et al*. 2000; Law *et al*. 2000). Further factors impeding seismic assessment include multiples (induced by the base of the overlying Upper Cretaceous chalk units) and the general low impedance contrast between sandstones and shales in this interval (Oakman 2005). Although seismic imaging quality has improved considerably in recent years (e.g. Hampson *et al*. 2010), alternative methods are required to assess the Lower Cretaceous units and to locate potential prospects. Attempts to delineate reservoir development have been made in the UK Central Graben (UKCG) with the use of regional 3D seismic and well data (Milton-Worssell *et al*. 2006, Fig. 1a), indicating significant potential for Lower Cretaceous sandstone development. Currently, other than local studies (e.g. Rossland *et al*. 2013), no published work has established a similar overview of Lower Cretaceous reservoir potential in the Norwegian sector of the Central Graben.

This study, therefore, aims to assess the potential for Lower Cretaceous sand bodies in the Norwegian Central Graben (NCG) and to link this interpretation to adjacent areas in the UK and to the Danish, German and Dutch parts of the North Sea Rift System (Southern Permian Basin area), as well as to the South Viking Graben (Fig. 1a).

GEOLOGICAL SETTING

The geological history of the Central North Sea has generated a diverse stratigraphic record, which is hereby described utilising a Norwegian stratigraphic nomenclature (Isaksen & Tonstad 1989; NPD 2017, Fig. 2). The oldest known units in the Norwegian Central Graben are of pre-Permian age; Silurian to Devonian metamorphic basement overlain by Old Red sandstones (Fossen *et al*. 2008). These units are followed, in stratigraphic order, by varied Carboniferous deposits (NPD 2014), Lower Permian Rotliegend sandstones and thick Upper Permian Zechstein evaporites plus dolomites. The halite sequences of the Zechstein have had a profound influence on the tectonic style; decoupling underlying and overlying strata (Hodgson *et al*. 1992; Stewart 2007; Ge *et al*. 2016; Jackson & Lewis 2016; Van Winden this volume). Lower Triassic Smith Bank Shales and Middle to Upper Triassic Skagerrak Sandstone deposition coincided with Late Triassic faulting along the inherited Caledonian structural grain (Bartholomew *et al*. 1993; UKDD 2007). This first rifting phase formed the general Central Graben structure, as these Triassic faults were partially reactivated in the Late Jurassic and Early Cretaceous (Rattey & Hayward 1993), although the main Triassic and Jurassic to Early Cretaceous depocenters do not precisely coincide (Erratt *et al*. 1999). Uplift and erosion due to an Early Jurassic mantle plume formed the Mid-Cimmerian unconformity in the Central North Sea (Underhill & Partington 1993). Middle Jurassic Bryne Formation coastal plain deposits succeed the hiatus (Bergan *et al*. 1989), followed by a second erosional surface. Eventual dome collapse coincided with the onset of renewed extension in the Northern North Sea (Graversen 2006), propagating into the Central North Sea during Late Jurassic times (Rattey & Hayward 1993). As rifting proceeded, sediment-starved deep marine basins developed (Copestake *et al*. 2003). This transgression is recorded in the syn-rift Jurassic Tyne Group by the Ula Formation shoreface sandstones and subsequent deep marine shales, including Mandal Formation source rock (Gautier 2005; Nøttvedt & Johannessen 2008).

Major extension ceased towards the end of the Kimmeridgian (Milton 1993), although a secondary phase of rift activity may have continued into the Earliest Cretaceous or Ryazanian in the Norwegian area, especially in the NCG (Gowers *et al*. 1993; Sears *et al*. 1993; Zanella *et al*. 2003; Ge *et al*. 2016). Rifting ceased as extensional stresses shifted to the proto-North Atlantic (Coward *et al*. 2003, Oakman 2005). Subsequently, post-rift thermal sag initiated and sediments began to cover the rift topography above the Base Cretaceous Unconformity (BCU) (Rattey & Hayward 1993). The first of these, the Cromer Knoll Group, contains mostly shales but also marly limestones (Tuxen Formation) plus shoreface to deep marine sandstones (Ran Sandstone units, Isaksen & Tonstad 1989). The sandstones represent potential reservoir bodies but their spatial and temporal extent is poorly constrained, being encountered in only a few wells. In the Aptian, another shift in tectonics and oceanography, the "Austrian event", occurred. This coincided with the onset of alpine compression and the opening of the North Atlantic, leading to more restricted basins and to the deposition of dark muds of the Sola Formation, overlain by calcareous Rødby Formation sediments (Garrett *et al*. 2000; Copestake *et al*. 2003).

Global sea level rise and a shift to a tropical climate in the Late Cretaceous saw the development of massive Upper Cretaceous chalk units in the North Sea sag basin (Surlyk *et al*. 2003). Thermal subsidence was, however, interrupted by local inversion pulses and associated Zechstein salt diapirism (Cartwright 1989; Johnson *et al*. 2005; Van Winden this volume). Renewed sediment input from the eroding North Atlantic rift shoulders gave rise to widespread turbidite systems in the Paleocene and Eocene. From the Oligocene onwards, thermal sag continued, concentrated in the NW of the NCG (Gowers & Sæbøe 1985), while the North Sea basin gradually filled in with thick clastic sequences.

ESTABLISHED LOWER CRETACEOUS UK RESERVOIRS

Three major sequences of sandstone deposits occur in the Inner Moray Firth (Copestake et al. 2003, Fig. 2); Ryazanian-Valanginian Punt sandstones SW of the Halibut Horst, Wick Sandstones south of the East Orkney High and Scapa Sandstones east of the Halibut High (locations in Fig. 1). In Barremian times, Coracle Sandstones of the Wick Fm occurred south of the East Orkney High and the Halibut High, whilst Scapa Sandstones were still present in the Witch Ground Graben (Jeremiah 2000). These units of the Lowermost Cretaceous (Ryazanian-Barremian play) were deposited during a phase of low sea level due to tectonic activity related to Austrian compression, ending with a major flooding event in the Barremian (Crittenden *et al*. 1997; Oakman 2005). Rejuvenated tectonic activity associated with the opening of the North Atlantic led to renewed sediment influx in the Aptian (Oakman 2005). During this phase, the Kopervik fairway was established (Law *et al*. 2000) along which large amounts of sand were transported from the East Orkney High to the outer Moray Firth, where the Britannia Field is situated (Ainsworth *et al*. 2000), before an Albian transgression diminished sand influx (Oakman & Partington 1998; Jeremiah 2000).

These deposits comprise of deep marine sandstones exhibiting a variety of depositional styles including hanging-wall slope-apron fans, linear channel complexes as part of a minibasin spilling system, or localised mass flow deposits and mud-dominated slurry-flow deposits (Jones *et al*. 1999; Argent *et al*. 2000). These sedimentary systems demonstrate a high degree of complexity regarding source and transport mechanisms (Eggenhuisen *et al*. 2010). Deposition was strongly influenced by the two Early Cretaceous tectonic phases mentioned above which uplifted and exposed highs and fault scarps, as documented to the north and northwest of the main depocenters (e.g. Halibut Horst, East Orkney High, O'Driscoll *et al*. 1990; Copestake *et al*. 2003; Jeremiah 2000, Fig. 1a). Tectonic activity furthermore modified the region's bathymetry and redirected sediment transport fairways (Jeremiah 2000; Aas *et al*. 2010). These deep marine sandstones represent Lower Cretaceous reservoirs in stratigraphic or combination structural/stratigraphic traps in for instance the Britannia, Scapa and Captain fields (McGann *et al*. 1991; Jones *et al*. 1999; Pinnock *et al*. 2003).

Although the Forties-Montrose High and Marnock Terrace formed barriers that separated the UKCG depocenters from the Moray Firth during the Early Cretaceous (Fig. 1a), it is possible to extend the Lower Cretaceous Moray Firth reservoir intervals into the UKCG (Milton-Worssell *et al*. 2006) where various wells encounter Lower Cretaceous sands. This well data, in combination with seismically-derived maps, allowed Milton-Worssell *et al*. (2006) to postulate the distribution of (mainly deep marine sandstone) bodies, sourced by the Western Platform, Forties-Montrose High and Jæren High, for both a Latest Ryazanian-Barremian play and the Aptian-Albian play in the UKCG. These plays are separated by the Fischschiefer Bed (Fig. 2), an organic-rich mudstone deposited during the Barremian flooding event, that is a regional seismic marker (Ainsworth *et al*. 2000). In this study, a similar division has been made between a "Latest Ryazanian" interval (near BCU-level) and an "Aptian-Albian" interval (near Top Lower Cretaceous level) to extend the scope into the NCG and to acquire a North Sea-wide overview (Fig. 2).

DATA AND METHODS

2D and 3D seismic datasets, provided by Shell Upstream International, combined with data from 474 wells were used to establish a structural framework in the study area (Fig. 1). The 3D data (extent: 11,400 km^2) are a compilation of the Norwegian Carmot dataset, covering the NCG, and part of the UK Megamerge dataset, covering a limited area part of the southern UKCG (Fig. 1). The quality is variable but typically consists of dominant frequencies of ca. 20-30 Hz, a wavelength of ca. 60 ms two-way travel time (TWT) with a resulting seismic resolution of ca. 15 ms TWT. This corresponds to ca. 30 m vertical resolution assuming an interval velocity of 3500 m/s. Water depths range from 40 to 100 m.

Data concerning 319 Norwegian wells in the study area were obtained from the Norwegian Petroleum Directorate (NPD) Factpages (NPD 2017). Additional well data for the UK and Danish sectors (119 and 41 wells, respectively) are from released well log and completion reports, well logs in the Shell archive (e.g. Boirie & Jeannou 1984; Statoil 1991) and published material (e.g Isaksen & Tonstad 1989, see table 1). Additional occurrences of Lower Cretaceous sandstones in UKCG wells are adopted from Milton-Worssell *et al*. 2006).

The following regional seismic horizons were mapped in two way time (TWT) on 3D seismic and calibrated with time-converted (via well checkshots and calibrated sonic logs) lithostratigraphically defined well tops from the Shell database and the NPD (Fig. 2):

- Base Cenozoic, (64 Ma);
- Top Lower Creteaceous (100 Ma);
- Base Cretaceous Unconformity (BCU, 140 Ma);
- Top Rotliegend (270 Ma).

Milton-Worrsell *et al*. (2006) mapped the Fischerbank Schiefer Bed, which defines the boundary between their two Lower Cretaceous plays (Fig. 2). In this study this marker could not be traced due to a lack of accurately constrained well picks. The time maps of the four interpreted seismic horizons are combined with existing digital TWT seismic horizon maps provided by Shell Upstream International that allow an extension of the survey further into British and Danish territorial waters (study area, Fig. 1). A time difference assessment between the seismic horizons yields isochron maps, illustrating where the thickest sequences within the Cenozoic, Upper Cretaceous and Lower Cretaceous intervals are situated, revealing the general structural trends in the study area (Figs. 3 and 4). Due to the large study area, no time to depth conversion was carried out which means these structural trends are somewhat qualitative.

Two more lithostratigraphically-contstrained horizons have been mapped in TWT on five additional regional 2D seismic transects to provide an additional link to previous studies (S1-S5, Figs. 1, 2, 5):

- Base Upper Jurassic (ca. 165 Ma);
- Top Zechstein (252 Ma).

Although the available seismic coverage does not include Denmark, an earlier study (Møller & Rasmussen 2003) provides a useful additional transect across the Danish border (S6, Fig. 5f). In combination with the seismic horizon time and isochron maps, these transects offer a detailed insight into the structural framework of the extended study area, revealing the locations of the main basins, highs, diapirs and faults (Figs. 3-5). Subsequently, the results of the seismic interpretation are integrated with published data from Copestake *et al.* (2003), Japsen *et al.* (2003), Milton-Worrsell *et al.* (2006) and Rossland *et al.* (2013) for an assessment of Lower Cretaceous reservoir potential in the extended study area, of which well data provide a first impression (Figs. 4 and 6).

The basic methodology applied by Milton-Worssell *et al.* (2006) has been adopted. Combined isochron maps of the extended study area indicate zones with thin Lower Cretaceous deposits, which were potentially exposed and prone to erosion during the Early Cretaceous (Fig. 7). At these places, well data provides the true thickness of the Lower Cretaceous sequence and the lithology in subcrop below the BCU. Devonian metamorphic rocks and volcanics, Rotliegend, Triassic Skagerrak, Middle Jurassic Bryne and Upper Jurassic Ula sandstones (Fig. 2) in subcrop indicate whether a specific locality was part of a potential sand source area during the Earliest Cretaceous. The presence of sand provenance areas is considered the most important factor controlling sandstone development since the Early Cretaceous was dominated by pelagic mud deposition (Fig. 2). This exercise is repeated for the Aptian-Albian reservoir interval, where the sand-prone lithologies in subcrop below the Top Lower Cretaceous horizon are charted (Fig. 8). The isochron maps subsequently allow the tracing of possible sediment transport fairways, by interpreting depocenters as drainage areas and barriers separating them as watersheds. Sediment transport is assumed to have followed the bathymetry given by the isochron maps, leading sediments from the highs to the depocenters. Thus, combining the isochron map, drainage and sand source areas; potential sand transport routes for the Latest Ryazanian and the Aptian-Albian are mapped (Figs 7 and 8). Well data allows a qualitative check of these interpretations: where sandstones occur in wells, a plausible link with a nearby sand source area can be inferred. If no such well data is available, sediment transport between source and depocenter remains speculative. It is recognised that the sandstones recorded in these wells are not necessarily linked to the postulated source areas and that those links would need to be proven via further investigation involving advanced seismic and well analysis techniques that are beyond the scope of this study.

STRUCTURAL FRAMEWORK INTERPRETATION

In general, a series of NNW-SSE orientated en-echelon (rift) basins, normal faults and tilted fault blocks follow the larger NW-SE Central Graben trend (Fig. 1, 3-5). The NCG structure is bounded by the Sørvestlandet High and the Ringkøbing-Fyn High to the east and by the Mid North Sea High to the south-west (Figs. 3-4).

The main depocenters, as identified on the isochron maps, are situated in the Breifflab Basin in the NW (Fig. 4a, 5, S1), where up to 8 km of subsidence has occurred (NDD 2012). However, the locations of these depocenters do not coincide with the thickest Upper Jurassic deposits in the SE part of the Feda Graben, Søgne Basin and Gertrud Graben (Erratt *et al*. 1999, Fig. 5, S5, S6). This discrepancy is a result of later differential thermal subsidence and sediment infill (Gowers & Sæbøe 1985). Normal faults are omnipresent in the area, but major differences in structural style occur between the Pre-Zechstein units, Triassic, Upper Jurassic, Lower Cretaceous syn-rift strata and post-rift infill. The Josephine High (Fig. 5, S1), Hidra High (Fig. 5, S2), Border High (Fig. 5, S4), Mandal High (Fig. 5, S5, S6) Cod Terrace (Fig. 5, S1) and Piggvar Terrace (Fig. 5, S5) represent Pre-Zechstein basement blocks forming major structural highs or terraces. Several large salt domes occur within the area (e.g. Fig. 5, S1).

Late Jurassic-Early Cretaceous rift structures

Due to Mid-Jurassic thermal doming and associated erosion, few Lower Jurassic units are preserved in the study area. In contrast, significant Upper Jurassic sediments, recording the latest North Sea rift phase, occur locally in extensional basins. These units are best developed in the south of the study area, where the Feda Graben, Gertrud Graben and Søgne Basin half-graben accommodate some 2 km of Upper Jurassic sequences (Fig. 5, S5, S6) as part of the large-scale left-stepping en-echelon Central Graben structure (Erratt *et al*. 1999, Fig. 1a). Many Triassic faults affect Upper Jurassic strata, indicating fault reactivation, e.g. the Skrubbe Fault and Coffee Soil Fault bounding the Feda Graben and Søgne Basin, respectively (Fig. 5, S5, S6). Rifting caused salt movement and diapirism which impacted Upper Jurassic sedimentation e.g. in the Søgne Basin.

Subsequently, the major Lower Cretaceous deposits are shifted westward compared to the Upper Jurassic depocenters (Figs. 5, S1, S3, S4). A distinct feature is the Early Cretaceous reactivation of the Pre-Zechstein half-graben west of the Border High, where Upper Jurassic or Triassic units are absent (Fig. 5, S4). Also striking is the lack of Early Cretaceous tectonic activity in the Søgne Basin; in contrast to significant Triassic and Upper Jurassic syn-tectonic units, little to no Lower Cretaceous sediments occur (Fig. 4b, 5, S5, S6).

The character of the Early Cretaceous basins varies considerably. The Border High and Breiflabb Basins are fault-bounded and show thickening towards the boundary faults, indicating syn-rift deposition (Fig. 5, S1, S4). Other rift-bounded basins are found west of the Hidra High (Fig. 5, S2), at well NO 2/4-10 (Fig. 5, S3) and west of the Mandal High (Fig. 5, S6). Yet the filling of pre-existing deep underfilled Jurassic basins as well as sediment compaction effects could partially account for these observations (Rattey & Hayward 1993;

Coward *et al*. 2003). At various localities, salt motion affected Early Cretaceous deposition: e.g. above the Hidra High (Fig. 5, S2) and at well NO 2/4-3 (Fig. 5, S4). In other parts of the study area, depocenters exhibit sag-type geometries, e.g. east of well UK 30/17B-3 and above the Hidra High (both in Fig. 5, S2), west of the NO 1/6-5 diapir (Fig. 5, S3) and in the Ål Basin (Fig. 5, S5, S6). Faults do not generally continue to the top of the Early Cretaceous, except for those associated with later tectonic inversion.

As such, cessation of rifting is shown to be diachronous. The westward shift of the Early Cretaceous depocenters with respect to the Jurassic rifts might indicate a change in extensional regime near the start of the Cretaceous, as proposed by previous authors (e.g. Erratt *et al*. 1999), before extension activity ceased altogether due to the opening of the young North Atlantic (Rattey & Hayward 1993).

Post-rift and tectonic inversion structures

The Late Cretaceous and Cenozoic units dominantly show gentle sag geometries along the NW-SE trend of the NCG, indicating further post-rift thermal subsidence. At the Breiflabb basin on the UK/Norwegian border, thermal subsidence was strongest creating a major Late Cretaceous/Cenozoic depocenter (Figs. 4a, 5, S1, 6a, Gowers & Sæbøe 1985). However, signs of inversion are also noted, for instance at the Lindesnes Ridge where Early Cretaceous syn-rift deposits are uplifted along Skrubbe Fault, (Figs. 5, S1, 6e). Inversion-related structures (inverted grabens and diapirs/salt domes) disturb not only the Upper Cretaceous deposits, but also Cenozoic strata (Figs. 3-5), indicating multiple inversion phases (Gowers *et al*. 1993).

LOWER CRETACEOUS RESERVOIR INTERPRETATION

Sandstone occurrences in Norwegian and Danish wells

In contrast to the UKCG, where numerous wells encounter Lower Cretaceous sandstones (Milton-Worssell *et al*. 2006), only three wells in the NCG area (from a total of 160 Lower Cretaceous penetrations) are reported to contain similar deposits (NPD 2017, Figs. 4b, 6). The sandstones in these wells are lithostratigraphically defined as Ran Sandstone units (NPD 2017) and, in contrast with the deep marine character of most equivalent Lower Cretaceous sandstones in the UK, are interpreted as shallow submarine fans (Isaksen & Tonstad 1989; Milton-Worssell *et al*. 2006).

Well NO 2/1-8 on the Cod Terrace contains a 4 m interval of Ran Sandstones, but no further details on lithology, or reservoir properties are publicly available (Fjellanger 1986; NPD 2013). These sandstones appear below the Hauterivian-Barremian Tuxen Fm and are, therefore, assigned to the Ryazanian reservoir interval (Fig. 2). Reference well NO 2/7-15 in the Feda Graben (Isaksen & Tonstad 1989, Fig. 4b) contains a 48 m thick Ran Sandstone sequence. Cores taken from the lowermost part of this succession are described as dominantly clay-rich siltstones with occasional micro-porosity and fractures with minor hydrocarbon shows (Phillips 1981). However, drill stem tests demonstrated the section to be tight (NPD 2017). The age of these Ran Sandstones is poorly constrained, but they are attributed to the Albian-Aptian reservoir interval due to their occurrence directly below the Aptian-Albian Sola Fm (Isaksen & Tonstad 1989, Fig. 2).

In well NO 3/7-3, east of the Mandal High (Fig. 4b), a 107 m thick Ran Sandstone sequence occurs on top of the BCU (NPD 2017). These deposits consist of a lower unit of dolomitic and glauconitic sandstones, interbedded with dolomitic and shaley layers, and an upper unit of massive coarse-grained sandstones with occurrences of chalky, sandy limestone, capped by carbonates containing some lignite (Verolles 1982). The massive sandstones (60-70% quartz) are cemented but represent good reservoir potential with porosities and permeabilities between 20-28 % and 0.5 to 10 D respectively (Verolles 1982; Boirie & Jeannou 1984). The NO 3/7-3 Ran Sandstones were deposited as lenticular sheets or slope apron bodies in a restricted and proximal, relatively shallow marine environment (100-200 m water depth, Verolles 1982), which evolved into an open marine setting towards the end of the Early Cretaceous (Boirie & Jeannou 1984). Since the Ran Sandstones are of Ryazanian age (Boirie & Jeannou 1984), they belong to the Latest Ryazanian reservoir interval.

Four other Norwegian wells encountering Ran Sandstone are situated to the NE, in block 17, at a considerable distance from the North Sea rift basins and outside the extended study area. The implications of these sandstone occurrences will be addressed in the South Viking Graben regional overview below.

In the Tail End Graben (Denmark), 9 m thick Lower Cretaceous subangular to subrounded and poor to moderately sorted, fine grained “Kira Sandstones” are found above BCU-level in the Amalie-1 well, probably deposited as part of a submarine fan system (Statoil 1991, Fig. 6). These sandstones are oil-bearing and of excellent reservoir quality with high porosities and permeabilities (0.213 and 319 mD, respectively) and a net-to gross ratio of 0.339 (Statoil 1991). Further Latest Ryazanian sandstones, although thinner, occur in the Tabita-1, Svane-1 and Iris-1 wells south of the Amalie-1 well (Figs. 4b). The Tabita-1 “Kira Sandstone equivalent” at the base of the Lower Cretaceous contains mostly claystone with very fine grained silt- and (quartz) sandstone striae (1-3 cm), as well as cross bedding with erosional surfaces (Bonde *et al*. 1994). A core from this interval contains conglomeratic intervals of unweathered, angular clasts of metamorphic basement material, as well as folded and disturbed mudstone beds. Both facies are indicative of slope process, whilst the lack of wave-related structures in the core suggests a depositional environment below storm wave base (Bonde *et al*. 1994). In the Svane-1 well, very fine to fine grained, subrounded, poorly sorted calcareous quartz sandstones with an argillaceous matrix and net-to-gross ratios up to 0.85 are found above the BCU (Thorsrud *et al*. 2002). The Iris-1 well contains various levels of thin sandstone in the Valhall Fm overlying the BCU which are “a few” meters thick (Britoil 1985). The cored material from this well is predominantly fine-grained and similar to that in the Tabita-1 well (Bonde *et al*. 1994). Further to the west, Lower Cretaceous (Latest Ryazanian-Early Hauterivian) fine to medium grained, poorly sorted sandstones, belonging to the Latest Ryazanian reservoir interval, are present in the Sten-1 well (Kern *et al*. 1983), making a total of 5 wells encountering Lower Cretaceous sandstones in the Danish part of the study area (Fig. 4b).

Latest Ryazanian reservoir distribution

An interpretation of the Latest Ryanazian reservoir interval is presented in Fig. 7 and depicts the sandstone occurrences in wells, potential source areas with sand-prone lithologies subcropping the BCU and sediment transport fairways to depocenters identified on the Lower Cretaceous isochron map.

Milton-Worrsell *et al*. (2006) demonstrated the potential for marine sandstone development in the Ryazanian-Barremian interval of the UKCG, with the Forties-Montrose High and Western Platform interpreted as provenance areas. Closer to the Norwegian-British border, sand-prone lithologies are found in subcrop below the BCU at the Josephine High (Skagerrak Fm), Auk Ridge (Rotliegend) and Argyll Field at the Mid North Sea High (Rotliegend, Ula Fm and Skagerrak Fm). These represent potential sand source areas for the surrounding depocenters where multiple well penetrations occur (Milton-Worrsell et al. 2006). The Auk Ridge is also the likely provenance area for the Lower Cretaceous Devil's Hole Sandstones to its west (Milton-Worssell *et al*. 2006). These scattered deposits are considered similar to the Norwegian Ran Sandstones (Isaksen & Tonstad 1989) and possibly represent a continuation of the Upper Jurassic syn-rift Fulmar/Ula shoreface or shelf deposits (Bisewski 1990; Johnson & Lott 1993; Copestake *et al*. 2003, Fig. 2). The UK Flora-Fife Trend area and the Danish Inge High contain Ula Fm and Rotliegend units in subcrop below the BCU. These are potential source areas for the sandstones in the Danish Sten-1 well (Kern *et al*. 1983), which is situated in a Lower Cretaceous depocenter (Fig. 7) and is postulated to be a deep marine deposit.

The 4 m thick unspecified sandstone layer in well NO 2/1-8 (NPD 2013) represents an isolated Ran Sandstone occurrence on the Cod Terrace (Fig. 2, 6). The most probable origin would be either the Mandal High or the Cod terrace, where well 7/11-8 encounters the Skagerrak Fm. in subcrop below the BCU (NPD 2017), indicating a possible small-scale sediment provenance area. Any material originating from the Scandinavian mainland to the NE would most likely be caught in the Norwegian-Danish Basin region, where major Lower Cretaceous depocenters are situated (Copestake *et al*. 2003, Fig. 1a). Similarly, sediments from the Josephine High would first have had to cross the Breifflab Basin depocenters (Fig. 7). However, the exact nature and provenance of these Ran Sandstones cannot be established with the data currently available.

The thickest Ran sandstones in the study area occur in well NO 3/7-3 (107 m, Fig. 6) and these relatively shallow to open marine sandstones were deposited just in the Søgne Basin (Verolles 1982; Boirie & Jeannou 1984), which was tectonically inactive during the Lower Cretaceous (Rossland et al. 2013, Figs. 5, S5, S6). The adjacent Mandal High and its metamorphic basement units were largely exposed during the Early Cretaceous (Verolles *et al*. 1982; Copestake *et al*. 2003; Rossland *et al*. 2013, Fig. 7, 9) and are the probable source for these proximal Ran Sandstones (Verolles 1982). Alternatively, Rossland *et al*. (2013) suggest, on the basis of dip directions, that these sandstones are related to a turbidite system sourced from the Rynkøbing-Fyn High to the east. It should however be stressed that their dip-meter data may be affected by post-sedimentary salt movement associated with the large salt dome below the Søgne Basin (Verolles 1982, Figs. 5, S5, S6), or could simply represent a deviation in transport direction as frequently observed within local submarine fan systems (e.g. Normark *et al*. 1979).

The presence of the thick Ran Sandstones in well NO 3/7-3 (Boirie & Jeannou 1984) indicate promising reservoir development in the area, yet none of the other wells in the vicinity encounter Lower Cretaceous sandstones (NPD 2017, Fig. 9). This is in accordance with the depositional character of the Ran Sandstone units described by Verolles (1982) and Boirie & Jeannou (1984), who suggest that reservoir bodies in the area, although potentially of significant thickness, may have a restricted lateral extent (Figs. 9). Furthermore, the Mandal High area is little studied, potentially harbouring reservoirs in various other stratigraphic intervals (Rossland *et al*. 2013, Fig. 10) and detailed analysis will be required to identify these.

In the east of the study area, the Kira Sandstones and their equivalents in the Amalie-1 and Tabita-1 wells (Fig. 6) probably represent submarine fan or slope deposits (Statoil 1991), associated with erosion at BCU-level and the nearby boundary fault between the Tail End Graben and the Ringkøbing-Fyn High (Bonde *et al*. 1994, Fig. 7). Although no rock samples are available from the Amalie-1 well, the metamorphic clasts in cores from the Tabita-1 well are reported to be similar to the basement rocks on the Ringkøbing-Fyn High and on the Mandal High (well NO 3/7-1) (Bonde *et al*. 1994). Possible supply from the Ringkøbing-Fyn High may have involved submarine erosion of the footwall basement, whereas alternative sediment transport from the Mandal High may have by-passed the NO 3/7-3 well and Amalie-1 well before reaching the Tabita-1 well location (Bonde *et al*. 1994, Fig. 7). The sand-prone intervals in the Svane-1 and Iris-1 wells are possibly correlatable to the Kira Sandstones (Bonde *et al*. 1994; Thorsrud *et al*. 2002), which, if correct, may indicate a regional deep marine fan system (Fig. 7). It should be noted however, that except for the Amalie-1 well, no Lower Cretaceous reservoir-quality sandstones are found. Yet a few localised sandy apron or lobe units may have developed as a continuation of the Jurassic deep marine sandstones in the area (Bonde *et al*. 1994; Nielsen *et al*. 2015). Similar deposits could also have developed in the Gertrud Graben and Feda Graben to the South and SW of the exposed Mandal High (Rossland *et al*. 2013), but there is currently no evidence to support this interpretation and identifying such reservoirs, if present, will be highly challenging.

In contrast to the UK and Danish Central Graben areas, no Latest Ryazanian sandstones appear in wells within the NCG proper (NPD 2017) and most Lower Cretaceous depocenters are isolated from the identified sand source areas (Fig. 7). However, various faults were still active, of which some could have exposed sand-prone lithologies to erosion. Of these, the Hidra High block next to the Breifflab Basin, where Rotliegend units are present in the footwall, is the best example (Figs. 5b, 7). However, it is possible that such smaller sand source areas (e.g. Argyll Field area: 10–100 km^2 and less for exposed fault scarps) might not have produced enough sand-prone material for reservoir-size deposits (*sensu* McArthur *et al*. 2016a). By contrast, the exposed Mandal High amounts to 500–600 km^2 and is associated with the thick Ran sandstones in well NO 3/7-3 and the postulated Amalie fan system, thus representing significant reservoir potential.

Aptian-Albian reservoir distribution

The interpretation of the Latest Ryazanian reservoir interval is presented in Fig. 8 and depicts the sandstone occurrences in wells, potential source areas with sand-prone lithologies subcropping the Top Lower Cretaceous and sediment transport fairways to depocenters identified on the Lower Cretaceous isochron map.

Towards the end of the Early Cretaceous, sandstone occurrences are rarely seen in UKCG wells (Milton-Worssel *et al*. 2006). However, important sediment provenance areas (e.g. the Forties-Montrose High, Auk Ridge, Josephine High) were still in place and exposed, providing sand influx into the adjacent depocenter as recorded in some penetrations (Milton-Worssell *et al*. 2006, Fig. 8). However, several of the smaller source areas were flooded and covered with Lower Cretaceous deposits (Cod Terrace and Inge High) and potential sourcing from fault scarps was strongly diminished with the cessation of rift activity. Other Ryazanian provenance areas were reduced but remained partially exposed towards the end of the Early Cretaceous as indicated by subcrop data (e.g. the Argyll Field area, Flora-Fife Trend, compare Fig. 8 with Fig. 7), yet no sandstone well occurrences are recorded in the adjacent Aptian-Albian depocenters.

Ran Sandstone units belonging to the Aptian-Albian reservoir interval are found in only one Norwegian well: NO 2/7-15 (Isaksen & Tonstad 1989, NPD 2017, Figs. 6, 8). These clay-rich silt/sandstones are somewhat isolated from the interpreted sediment provenance areas. The Flora Field area, where the Rotliegend is found in subcrop below the Upper Cretaceous chalk deposits, is proposed as the most likely origin of these units (Fig. 8). However, the character of NO 2/7-15 Ran Sandstones remains poorly constrained and demands further assessment.

It should be noted that the wells in the Søgne Basin area, where thick Ryazanian Sandstones were previously deposited (well NO 3/7-3), record only mudstone and chalky deposits (Rossland *et al*. 2013; NPD 2017). Also, the potential Amalie fan system in the Danish Tail End Graben to the south is absent in well reports. Yet the Mandal High was still prone to erosion during the Aptian-Albian, as indicated by metamorphic basement and Bryne Fm subcropping the Upper Cretaceous chalk units (wells NO 2/6-5, NO 3/7-1 and West-Lulu 4, Mærsk 1987; NPD 2017). In addition, large parts of the Ringkøbing-Fyn High have no or thin (a few meters) Lower Cretaceous cover (Japsen *et al*. 2003). Both highs may, therefore, have produced sand-prone material leading to localised reservoir development (Fig. 8), although there is currently no evidence to support this suggestion.

Overall, the Aptian-Albian reservoir interval provides significantly less potential for Lower Cretaceous sandstone deposits than the Latest Ryazanian, due to the drowning of sand source areas. Still, the Ran Sandstone present in well NO 2/7-15 and the sandstone occurrences in various other wells in the UKCG indicate some reservoir potential.

POTENTIAL ANALOGUE SETTINGS IN THE SOUTHERN PERMIAN BASIN AREA

This study shows that the UKCG and NCG harbour potential for Lower Cretaceous sandstone reservoir units suggesting further exploration possibilities. As the Central Graben structure continues south into Danish, German and Dutch territorial waters (Figs. 1, 11), where the geological setting was quite similar during the Early Cretaceous (Voigt *et al*. 2008; Pharaoh *et al*. 2010), it would be worthwhile to extend the scope of a future case study to these areas.

In Denmark for example, the Ringkøbing-Fyn High along the Eastern margin of the Tail End Graben has no or limited Upper Jurassic to Lower Cretaceous sedimentary cover (Japsen *et al*. 2003), and is known to have been the source of various Late Jurassic fan deposits (Johannessen & Andsbjerg 1993; Andsbjerg & Dybkjær 2003). Such conditions are likely to have continued into at least the Earliest Cretaceous, as illustrated by the deposition of Vyl sandstones (Figs. 2, 11a). These submarine fan units with moderate reservoir potential are found adjacent to the Coffee Soil Fault and were supplied by the Ringkøbing-Fyn High (Michelsen *et al*. 2003, Fig. 11a). In addition, the Lower Cretaceous chalks of the Tuxen Fm. form the reservoirs in the Danish Valdemar and Adda fields (Copestake *et al*. 2003; Jakobsen *et al*. 2005, Fig. 2) indicating another attractive target for continued exploration in the area.

Further to the south, the German and Dutch sectors of the Central Graben are flanked by the Schill Grund High to the east and the Step Graben and Cleaver Bank High to the west (Fig. 11a), areas which were exposed highs during the Late Jurassic and the Early Cretaceous (Pharaoh *et al*. 2010). However, intense Late Cretaceous and Cenozoic basin inversion has caused significant erosion (De Jager 2007) and most of the Lower Cretaceous in the southern sector of the Dutch Central Graben was removed. In the northern sector of the Dutch Central Graben, where inversion and associated erosion was less drastic (Dronkers & Mrozek 1991), Lower Cretaceous sediments are better preserved and hydrocarbon-bearing Scruff sandstones are found (De Jager 2003; De Jager & Geluk 2007, Fig. 2). Additionally, the adjacent Terschelling Basin, where moderate inversion is recorded (Verweij & Witmans 2009) contains relatively thick Lower Cretaceous deposits (Duin *et al*. 2006; EBN *et al*. 2015).

On the southern fringes of the Southern Permian Basin, the Broad Fourteens Basin and West Netherlands Basin form a continuation of the Lower Cretaceous North Sea basins (Fig 11a). Although these basins also underwent strong post-rift inversion (Van Wijhe 1987; De Jager 2003), significant parts of the Lower Cretaceous deposits are preserved in the area (over 900 m thick locally, Duin *et al*. 2006) and contain various hydrocarbon fields (De Jager & Geluk 2007). Similar to the situation in the Moray Firth, the associated reservoirs are documented to be visible on seismic due to a relatively thin Upper Cretaceous-Cenozoic overburden (Oakman 2005). The Early Cretaceous depositional environment was, however, rather different from the situation in the Central Graben and Moray Firth. Instead of isolated shale-dominated basins, receiving limited sand influx from small exposed highs nearby, the area received ample sediment input from the large London-Brabant Massif to the south (Jeremiah *et al*. 2010, Fig. 11a). Therefore, extensive continental to shallow marine shelf clastics were deposited in relatively shallow basins, in contrast with the deep marine basin settings in the Central and Northern North Sea (Figs. 2, 11). The abundance of sand-prone material in the depositional systems on the fringe of the Southern Permian Basin could potentially have fed submarine fans in the rift depocenters further north. The area experienced tectonically-induced rejuvenation of clastic input, progradation and the development of a widespread shelf system at the K30 sequence boundary, which is associated with increased Hauterivian deep marine reservoir development in the Moray Firth (DeVault & Jeremiah 2002). However, except for the Lower Barremian (Wanneperveen) turbidite units found in association with the Friesland Platform near the Dutch-German border (Jeremiah *et al*. 2010, Fig. 11a), no such deposits are recorded in the Southern Permian Basin. This scarcity of deep marine sand development may be related to the area's relatively gentle bathymetry during the Early Cretaceous (Fig. 11a) although various other factors are known to affect turbidite systems such as shelf width, surrounding geomorphology and hinterland lithologies (Martinsen *et al*. 2005; Mudge 2014).

ANALOGUE SETTINGS IN THE SOUTH VIKING GRABEN AREA

Another potential analogue region to the NCG is the South Viking Graben (SVG, Fig. 11). In contrast to the Southern North Sea, the area was associated with a deep marine setting (flanked by exposed highs) during the Earliest Cretaceous (Fig. 11a). Shallow marine or terrestrial sandstones were deposited on the Utsira High, forming parts of the reservoirs in the Edvard Grieg and Johan Sverdrup fields (NPD 2017) and may be directly comparable to the Mandal High in the NCG (Rossland *et al*. 2013). The SVG is documented to include Upper Jurassic turbidites (Partington *et al*. 1993; Fraser *et al*. 2003; Jackson *et al*. 2011). The associated Fladen Ground Spur, Crawford Spur and Utsira High sand provenance areas continued to be exposed in the earliest Cretaceous (Copestake *et al*. 2003, Fig 11a). However, no Earliest Ryazanian deep marine sands are reported from the SVG area, potentially providing exploration opportunities.

The situation was different during the Aptian, where Skiff Sandstone units are reported along the fringes of the Fladen Ground Spur and the Crawford Spur (Johnson & Lot 1993; Johnson *et al*. 2005, Fig. 11b). To the south, the Kopervik fairway supplied the reservoirs of the giant Britannia Field with sands derived from the East Orkney High in the west (Jeremiah 2000). Oakman (2005) suggests that these deep marine sands represent a fundamentally different depositional system for the Aptian-Albian interval, rather similar to the Cenozoic situation and involving sediment transport over long distances sourced by the exposed North Atlantic rift shoulders, in contrast to the preceding confined Upper Jurassic turbidite fans. The Kopervik system is, however, separated from the SVG by a halokinetically-induced high that was in place throughout the Early Cretaceous, so that potential sandstone deposits in the SVG can only be derived from the adjacent highs (Bisewski 1990, Fig, 11). Further to the north, in the North Viking graben, deep marine slumps of Albian age form reservoirs of the Agat field Skibeli *et al*. 1995) but these deposits were derived from the main Scandinavian massif (Gulbrandsen & Nyborkken 1991), whereas the SVG remained relatively isolated.

Other wellbore calibrated sandstone occurrences in the area are reported from the Åsta Graben, SE of the Utsira High (3-6 in Fig. 11b, Table 1). These Ran Sandstone units all occur in the uppermost part of the Lower Cretaceous, directly underneath the Upper Cretaceous chalk deposits and were likely deposited in a shallow marine environment (Olsen 1979; Isaksen & Tonstad 1989).

POTENTIAL METHODS FOR FURTHER DETAILED RESERVOIR INTERPRETATION

As demonstrated by Milton-Worssell *et al*. (2006), detailed seismic analysis is required to distinguish potential reservoir units. However, the presence of thick Upper Cretaceous chalk and the low impedance contrasts between Cromer Knoll shales and sandstones renders seismic imaging of any relatively thin (typically less than 30 m) Lower Cretaceous sandstone reservoir problematic. To do so requires good quality 3D seismic data combined with an understanding of the likely depositional systems to be encountered (Crittenden *et al*. 1998; Law *et al*. 2000; McKie *et al*. 2015). With such data available, sedimentary systems such as deep marine fans may be traceable on time slice amplitude maps (e.g. Posamentier & Kolla 2003; Martinsen *et al*. 2005; Kilhams *et al*. 2011; 2014a). Amplitude versus offset (AVO) techniques could help to distinguish differences in lithology and reservoir fluid content (e.g. Oakman 2005; Veeken & Rauch-Davies 2006; Milton-Worssell *et al*. 2008; Othman *et al*. 2017). Such a study would be recommended for the Tail End Graben area, as there is potential for small-scale reservoir development. Furthermore, the seismic response of Lower Cretaceous sandstone well occurrences in the NCG, as well as the UKCG where sandstones are more common (Milton-Worssell *et al*. 2006), should be compared to seismic facies in undrilled depocenters. Detailed seismic sequence stratigraphy of Lower Cretaceous depocenters could allow the identification of sea-level driven erosional unconformities on highs, associated with lowstand fans systems in basinal areas (*sensu* Posamentier & Vail 1988).

Methods to further assess sand source areas and to localise associated shallow to deep marine sandstones might include palynological (or similar biostratigraphic) analysis of cored wells to determine to what degree a high was exposed (e.g. O'Driscoll *et al*. 1990; Mudge & Jones 2004; McArthur *et al*. 2016a). Since cores from wells NO 2/7-15 and NO 3/7-3 are available (NPD 2017), magnetic analysis could provide sediment transport directions of these specific Early Cretaceous sandstone occurrences (Hailwood & Ding 2000). Additional petrological and geochemical analysis of heavy minerals (e.g. garnets or zircons) might reveal their provenance area (e.g. Morton *et al*. 2005; Kilhams *et al*. 2014b; Nielsen *et al*. 2015), if cuttings/cores of nearby sand source areas are available (e.g. well NO 3/7-1 on the Mandal High and wells NO 3/7-3 and Tabita-1 in the Søgne Basin and Tail End Graben, respectively; Verolles 1982; Bonde *et al*. 1994, Fig. 7). Furthermore, it will be important to consider the factors influencing the behaviour and geometries of shoreface systems and deep marine fans (e.g. sand-to-mud ratio, flow discharge, slope gradient, sea level changes and fault activity) and where sand deposits occur in these systems (e.g. Posamentier & Kolla 2003; Martinsen *et al*. 2005; McKie *et al*. 2015; McArthur *et al*. 2016b). Recently developed software for the simulation of turbidite deposition in combination with paleorelief reconstructions on 3D seismic could be a powerful tool to predict the distribution of deep marine fans (Aas et al. 2010).

CONCLUSIONS

Here a structural framework of the NCG area has been presented. This reflects a diverse geological history including Triassic extension and salt movement, Late Jurassic to Early Cretaceous rifting and subsequent basin inversion with salt diapirism. Late Jurassic rifting was most intense in the south of the study area, while Early Cretaceous rifting was more important in the north, possibly representing an Early Cretaceous change in tectonic regime before rifting halted altogether. An assessment of the Lower Cretaceous indicates fair potential for reservoir development. Although the study area is isolated from a large hinterland, local sediment sources and potential sediment transport routes are identified. Most potential is expected around the exposed highs in Ryazanian times, while many sand source areas were drowned at the end of the Early Cretaceous (Aptian-Albian). The underexplored Mandal-High area, where restricted shallow marine sandstone deposits around the exposed Mandal High and in the Søgne Basin provide the best potential, is suggested for further focus. Similar depositional environments could have existed around other exposed highs (e.g. Josephine High, Auk Ridge), although they may have been too small to have produced significant reservoir units. Furthermore, the postulated Amalie fan system in Denmark illustrates the possibilities for good quality deep marine sandstones, which may have also formed in the depocenters south and SW of the Mandal High. Analogous settings to those in the study area are also recognised in the Southern Permian Basin area to the south and the South Viking Graben to the north, further analysis of the Lower Cretaceous reservoir intervals of these areas would be an interesting next step. A detailed effort including the use of advanced seismic techniques and detailed well analysis will be necessary to accurately define such reservoirs, if present. The discovery of the Edvard Grieg and Johan Sverdrup fields illustrates the importance of continued exploration, especially the re-assessment of available well and seismic data, in the context of this mature hydrocarbon province (Jørstad 2012).

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TABLE CAPTION

Table 1. List of sources for well data

Type of data	Well	Datasource
Lithostratigraphic tops for seismic interpretation	Norway	NPD 2017, Shell database
	UK	Shell database
	Denmark	Shell database
Well shown in well panel Fig. 6	UK 30/11b-1, UK 29/5a-5	Milton-Worssell *et al.* 2006
	NO 2/1-8	Fjellanger 1986; NPD 2013
	NO 2/7-15	Phillips 1981; Isaksen & Tonstad 1989
	NO 3/7-3	Verolles 1982; Boirie & Jeannou 1984; NPD 2017
	Amalie-1	Statoil 1991
Other well data described in text and other images	Norway	NPD 2017
	NO 7/3-1	NPD 1979a; Strass 1979
	NO 17/10-1	NPD 1979b; Olsen 1979
	NO 17/11-1	A/S Norske Shell 1968
	NO 17/11-2	Provan 1976
	UKCG	Milton-Worssell *et al.* 2006
	Denmark (general)	Shell database
	Sten-1	Kern *et al.* 1983
	Tabita-1	Bonde *et al.* 1994
	Iris-1	Britoil 1985; Bonde *et al.* 1994
	Svane	Thorsrud *et al.* 2002
	West Lulu-4	Mærsk 1987
BCU and Top Lower Cretaceous subcrop data	e.g. NO 7/11-8, NO 3/7-1	NPD 2017; Shell database

FIGURE CAPTIONS

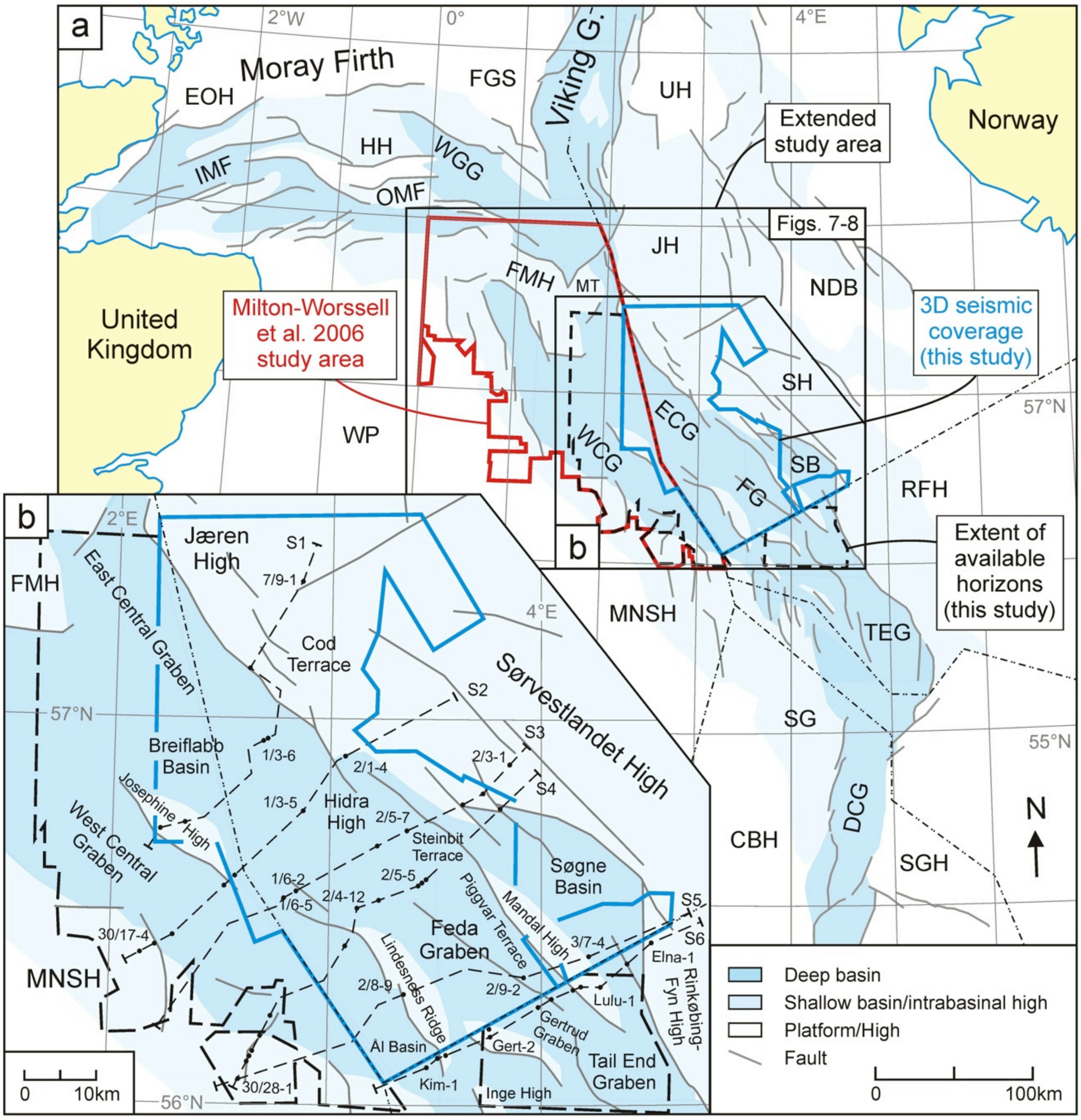


Fig. 1. (**a**) Structural map of the Late Jurassic Central Graben depicting the study area (Norwegian Central Graben area and parts of the UK Central Graben) and the adjacent UK Central Graben study area of Milton-Worssell *et al*. (2006), that in combination define the extended study area. (**b**) Detailed map of the study area, indicating seismic coverage (blue) and the extent of available seismic depth maps (thick dotted outline). Dotted lines indicate interpreted seismic sections S1-S6 (Fig. 5). CBH: Cleaver Bank High, DCG: Dutch Central Graben, EOH: East Orkney High, NDB: Norwegian-Danish Basin, ECG: East Central Graben, FG: Feda Graben, FGS: Fladen Ground Spur, FMH: Forties-Montrose High, HH: Halibut High, IMF: Inner Moray Firth, JH: Jæren High, MNSH: Mid North Sea High, MT: Marnock Terrace, OMF: Outer Moray Firth, RFH: Ringkøbing-Fyn High, SB: Søgne Basin, SH: Sørvestlandet High, SG: Step Graben, SGH: Schill Ground High, TEG: Tail End Graben, UH: Utsira High, WCG: West Central Graben, WGG: With Ground Graben, WP: Western Platform. Modified after Fraser *et al*. (2003), Milton-Worssell et al. (2006) and Pharaoh *et al*. (2010).

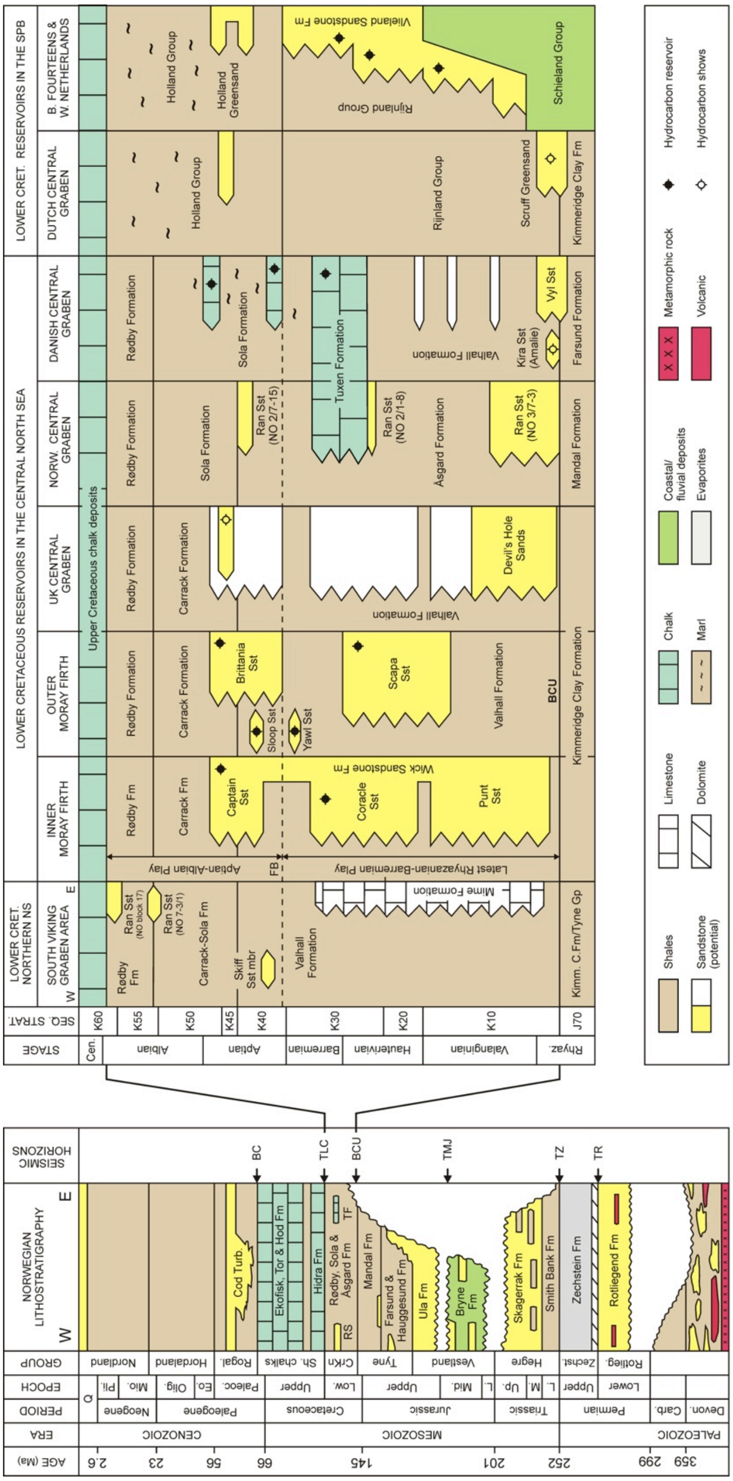


Fig. 2. Norwegian lithostratigraphy for the study area (left) and overview of Lower Cretaceous reservoirs in the Central North Sea (right). CrKn: Cromer Knoll Group, FB: Fischerbank Schiefer, NS: North Sea, SPB: Southern Permian Basin. Seismic horizon abbreviations from top to bottom: BC: Base Cenozoic, TLC: Top Lower Cretaceous, BCU: Base Cretaceous Unconformity, TMJ: Top Middle Jurassic, TZ: Top Zechstein, TR: Top Rotliegend. Modified after Vollset & Doré (1984), Van Wijhe (1987), Isaksen & Tonstad (1989), Wong *et al*. (1989), Copestake *et al*. (2003), Milton-Worssell *et al*. (2006), De Jager & Geluk (2007), Jakobsen *et al*. (2005); Herngreen & Wong (2007), UKDD (2007), Wong (2007), NDD (2012). Geological timescale dates after Walker *et al*. (2012).

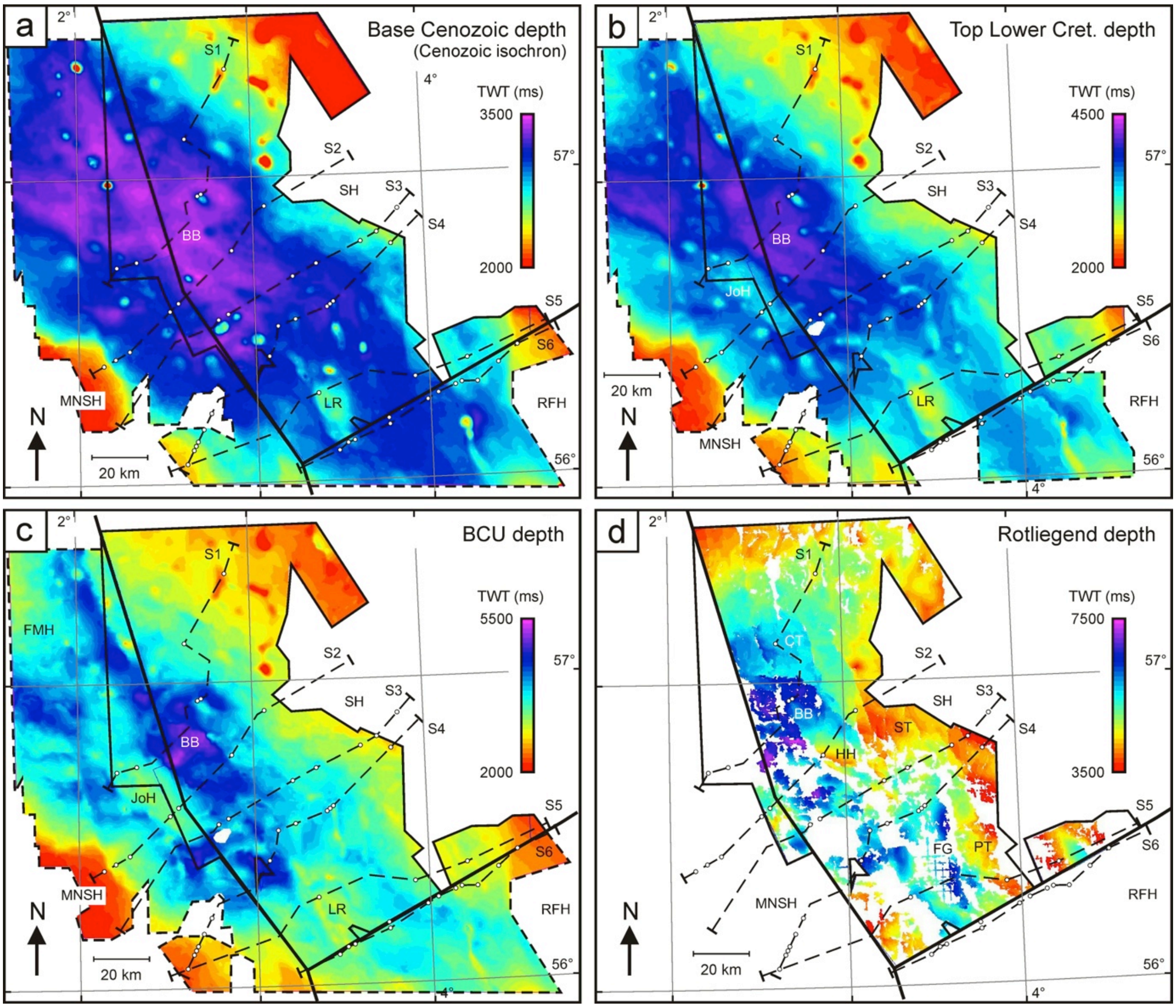


Fig. 3. Time depth maps of four regional horizons in the study area: (**a**) Base Cenozoic; (**b**) Top Lower Cretaceous; (**c**) Base Cretaceous Unconformity (BCU); (**d**) Top Rotliegend. Note that the Base Cenozoic time depth map (a) is also the Cenozoic isochron map and that the Top Rotliegend map is incomplete due to locally poor seismic quality. Dotted lines indicate the trace of interpreted transects S1-S6 and white dots indicate well locations along these transects (see Fig. 5). Solid outlines indicate the extent of the 3D seismic survey. Dashed outlines indicate the extent of the available previously interpreted seismic horizons in the UK and Denmark (see Fig. 1). BB: Breiflabb Basin, CT: Cod Terrace, FG: Feda Graben, HH: Hidra High, JoH: Josephine High; FMH: Forties-Montrose High; MNSH: Mid North Sea High, LR: Lindesness Ridge, PT: Pigvarr Terrace, RFH: Ringkøbing-Fyn High, SH: Sørvestlandet High, ST: Steinbit Terrace.

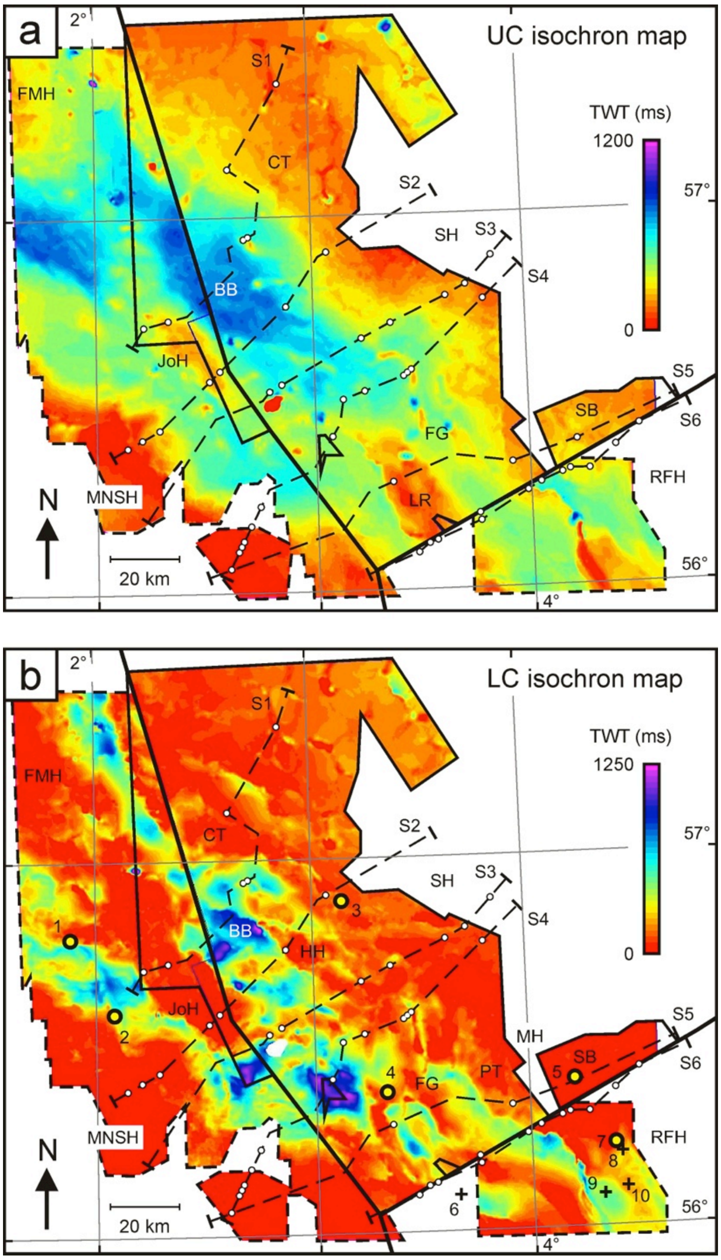


Fig. 4. Isochron maps showing the location and geometry of depocenters in the study area in Two-way travel time. (**a**) UC: Upper Cretaceous isochron map; (**b**) LC: Lower Cretaceous (Cromer Knoll Group). Dotted lines indicate the trace of interpreted transects S1-S6 and wells along these transects (see Fig. 5). Solid outlines indicate the extent of the 3D seismic survey. Dashed outlines indicate the extent of the available previously interpreted seismic horizons in the UK and Denmark (see Fig. 1). The larger yellow dots indicate >3 m sand occurences in wells within the study area, whereas crosses indicate sandstone traces (<3 m thickness). Wells: (1) UK 29/5a-5, (2) UK 30.11b-1, (3) NO 2/1-8, (4) NO 2/7-15, (5) NO 3/7-3, (6) Sten-1, (7) Amalie-1, (8) Tabita-1, (9) Iris-1, (10) Svane-1. BB: Breiflabb Basin, CT: Cod Terrace, FG: Feda Graben, FMH: Forties-Montrose High, HH: Hidra High, JoH: Josephine High, MH: Mandal High, MNSH: Mid North Sea High, LR: Lindesness Ridge, PT: Pigvarr Terrace, RFH: Ringkøbing-Fyn High, SB: Søgne Basin, SH: Sørvestlandet High.

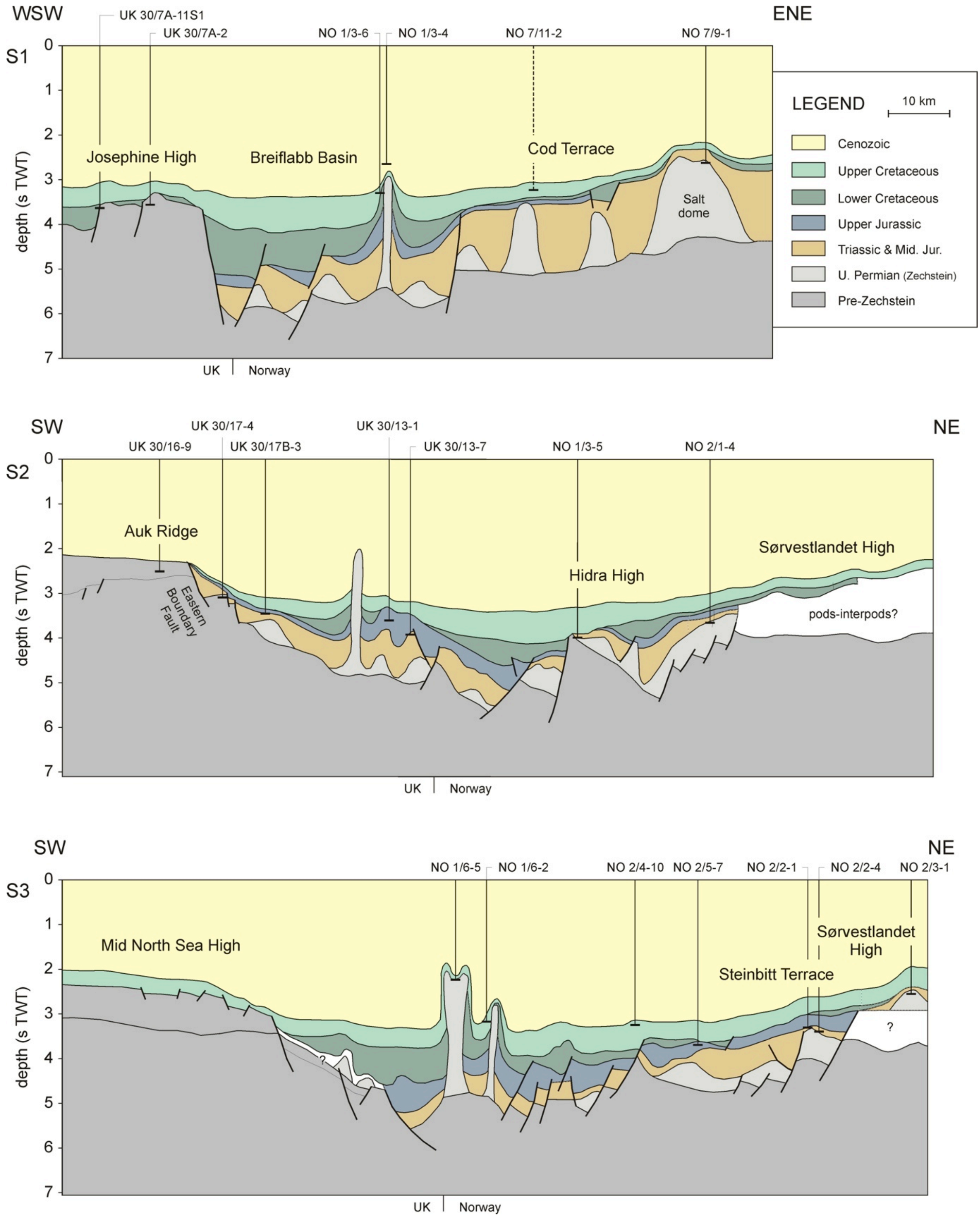


Fig 5. Interpreted seismic sections S1-S3. UK: United Kingdom. For section locations see Fig. 1b. Reference datum is mean sea level.

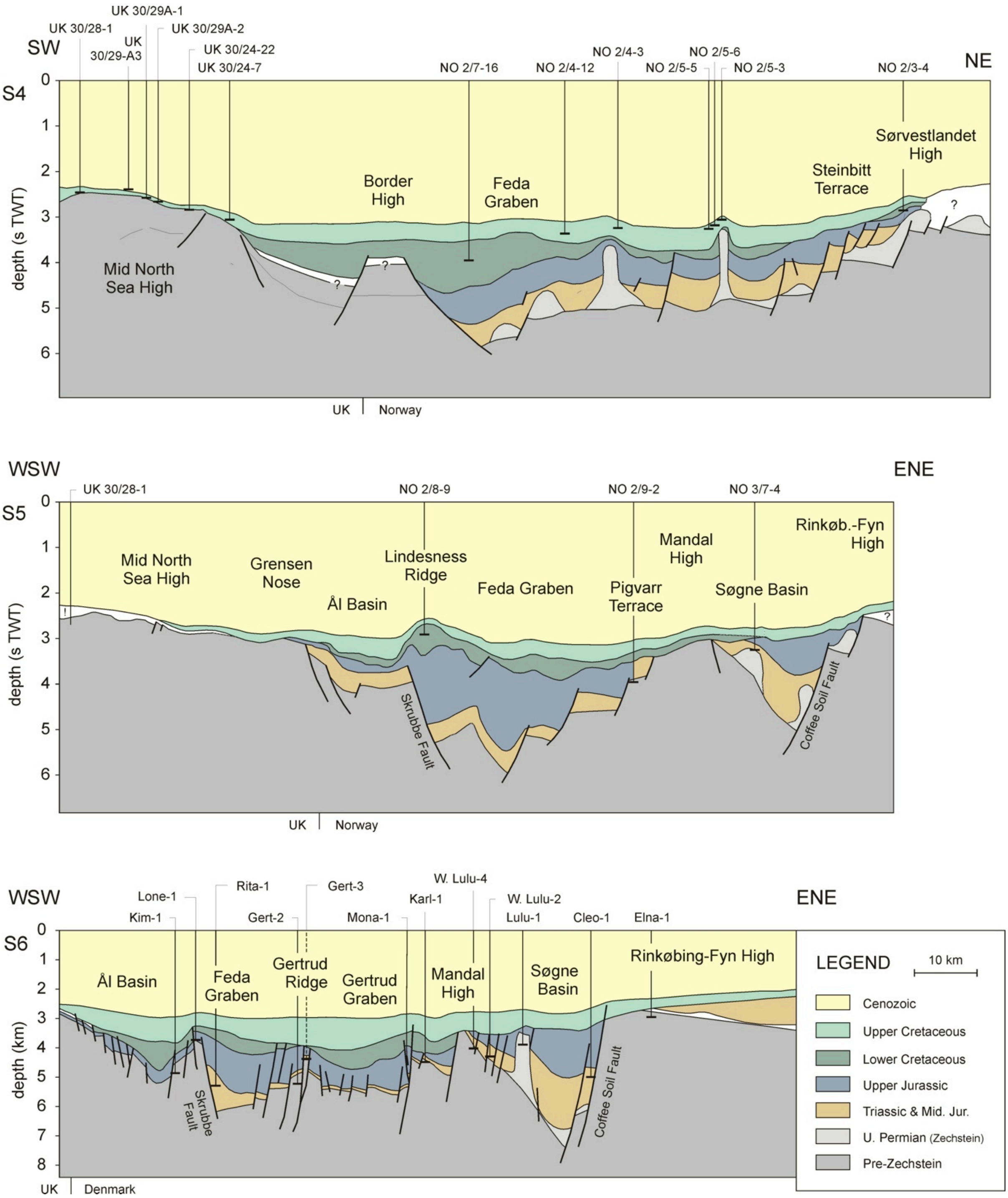


Fig 5. (continued) Interpreted seismic sections S4-S6. UK: United Kingdom. For section locations see Fig. 1b. Section S6 modified after Møller & Rasmussen (2003). Reference datum is mean sea level.

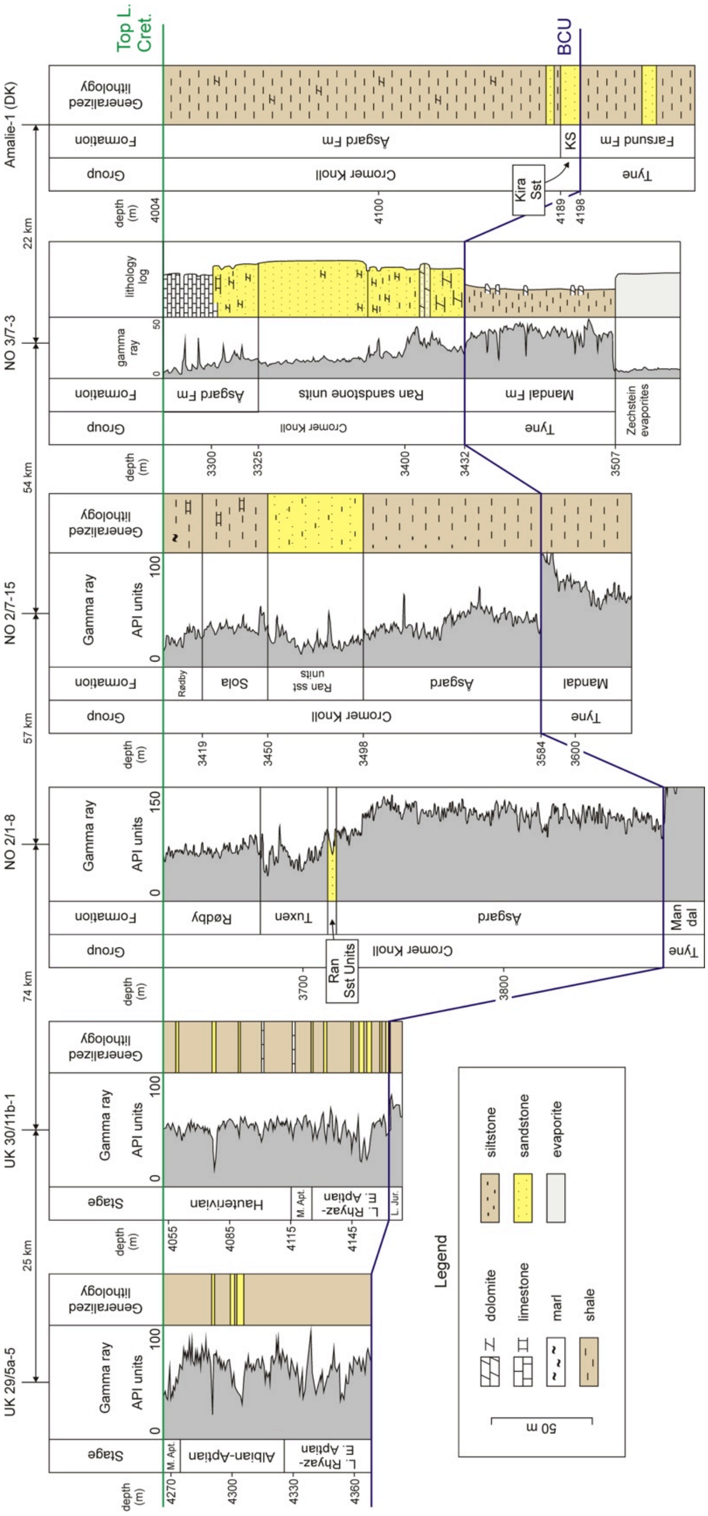


Fig. 6. Well data from wells UK 30/11b-1 and UK 29/5a-5 (modified after Milton-Worssell *et al*. 2006), NO 2/1-8 (modified after NPD 2013), NO 2/7-15 (modified after Isaksen & Tonstad 1989), NO 3/7-3 (modified after Boirie & Jeannou 1984) and Amalie-1 (DK, modified after Statoil 1991), all containing Lower Cretaceous (Ran/Kira) Sandstone units and hung off Top Lower Cretaceous level (Fig. 2). No lithology data are available for well NO 2/1-8. No Gamma Ray data available for well Amalie-1. Locations shown in Fig. 4b.

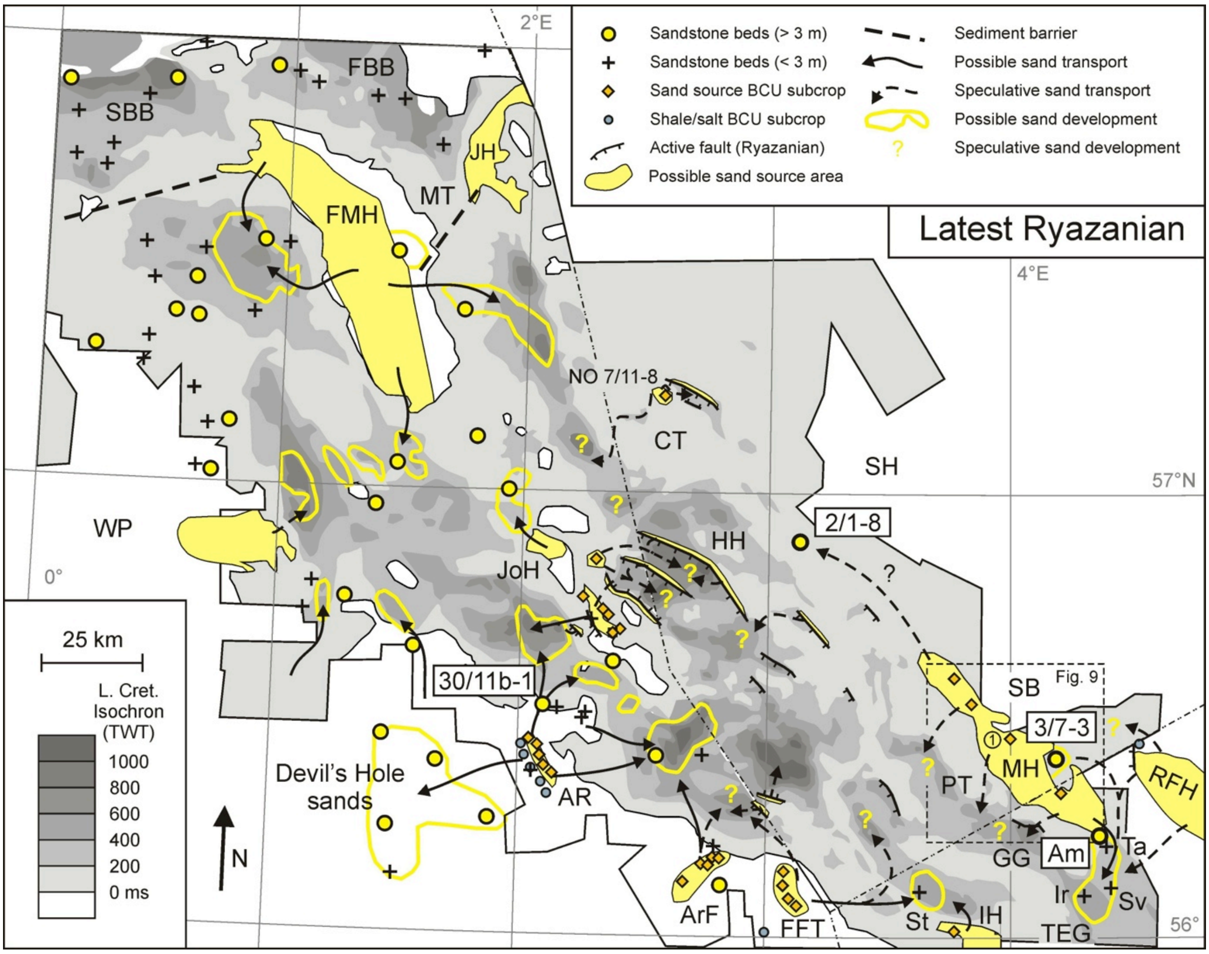


Fig. 7. Interpretation of reservoir potential in the extended study area for the Latest Ryazanian (BCU-level). Well data, possible sand source areas, Ryazanian fault activity, possible sediment transport fairways and areas of possible sandstone development are projected on top of the Lower Cretaceous isochron map. Well identifiers are Ir: Iris-1, St: Sten-1, Sv: Svane-1, Ta: Tabita-1, (1): well NO 3/7-1. AR: Auk Ridge, ArF: Argyl Field, CT: Cod Terrace, FBB: Fisher Bank Basin, FFT: Flora-Fife Trend, FMH: Forties-Montrose High, GG: Gertrud Graben, HH: Hidra High, IH: Inge High, JH: Jæren High, JoH: Josephine High, MH: Mandal High, MT: Marnock Terrace, PT: Piggvar Terrace, RFH: Ringkøbing-Fyn High, SB: Søgne Basin, SBB: South Buchan Basin, SH: Sørvestlandet High, TEG: Tail End Graben, WP: Western Platform. Modified after Japsen *et al*. (2003), Milton-Worssell *et al*. (2006) and Rossland *et al*. (2013).

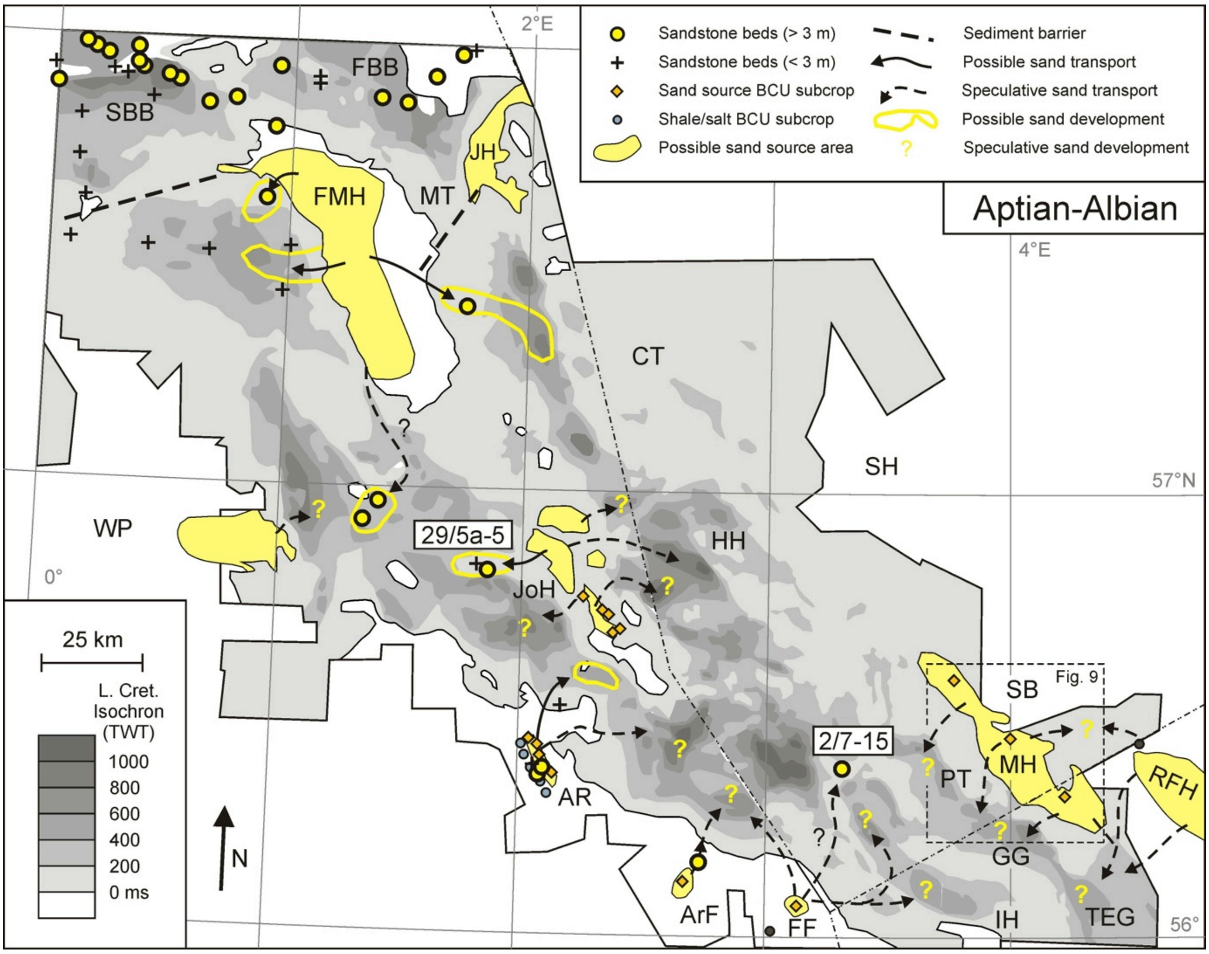


Fig. 8. Interpretation of reservoir potential throughout the extended study area for the Aptian-Albian (near-Top Lower Cretaceous level). Well data, possible sand source areas, interpreted possible sediment transport fairways and areas of possible sandstone development are projected on top of the Lower Cretaceous isochron map. AR: Auk Ridge, ArF: Argyl Field CT: Cod Terrace, FBB: Fisher Bank Basin, FF: Flora Field, FMH: Forties-Montrose High, GG: Gertrud Graben; HH: Hidra High, IH: Inge High, JH: Jæren High, JoH: Josephine High, MH: Mandal High, MT: Marnock Terrace, PT: Piggvar Terrace; RFH: Ringkøbing-Fyn High, SB: Søgne Basin, SBB: South Buchan Basin, SH: Sørvestlandet High, TEG: Tail End Graben, WP: Western Platform. Modified after Japsen *et al*. (2003), Milton-Worssell *et al*. (2006) and Rossland *et al*. (2013).

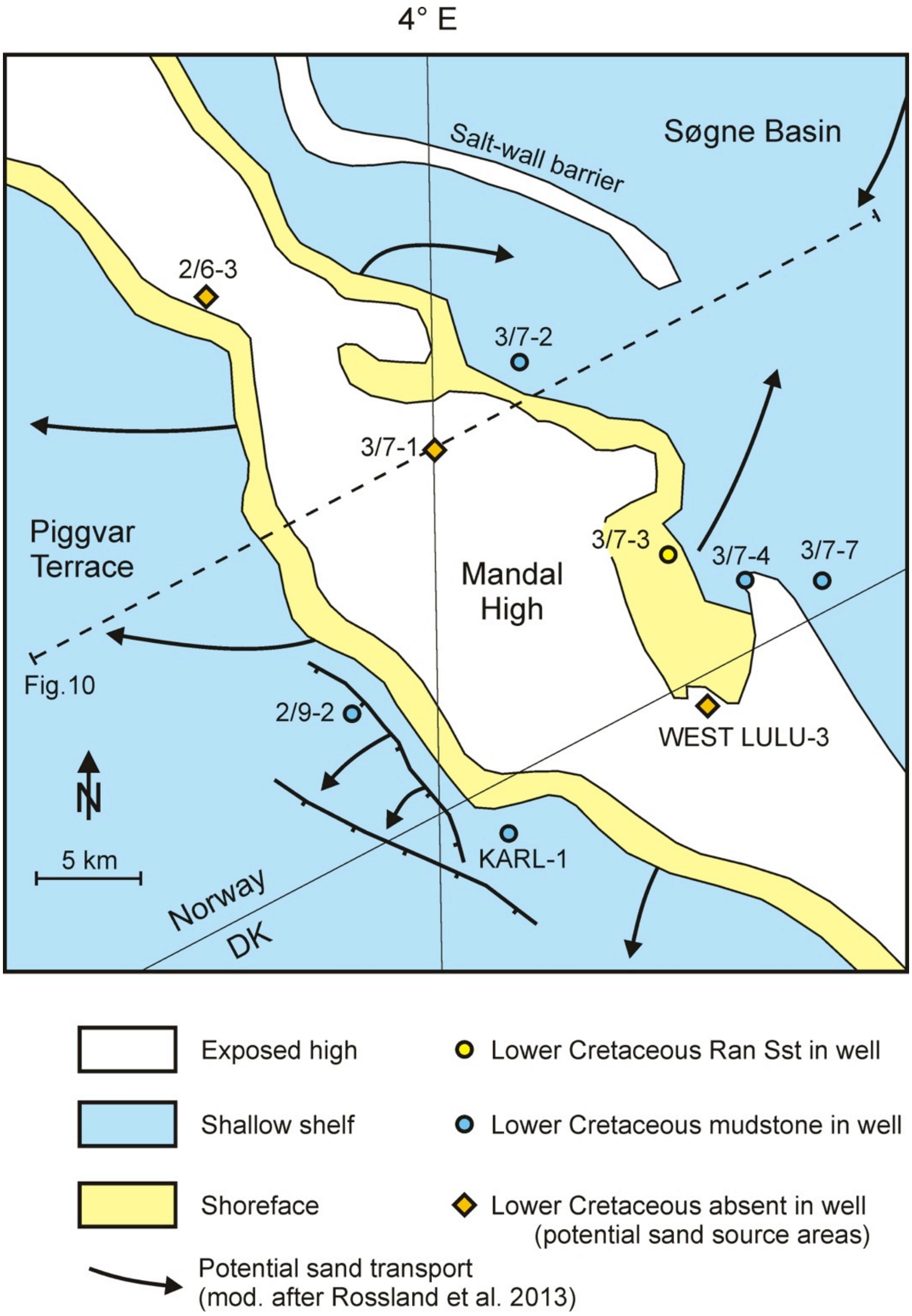


Fig. 9. Proposed Early Cretaceous paleogeographic situation around the Mandal High area. Image modified after Rossland *et al*. (2013).

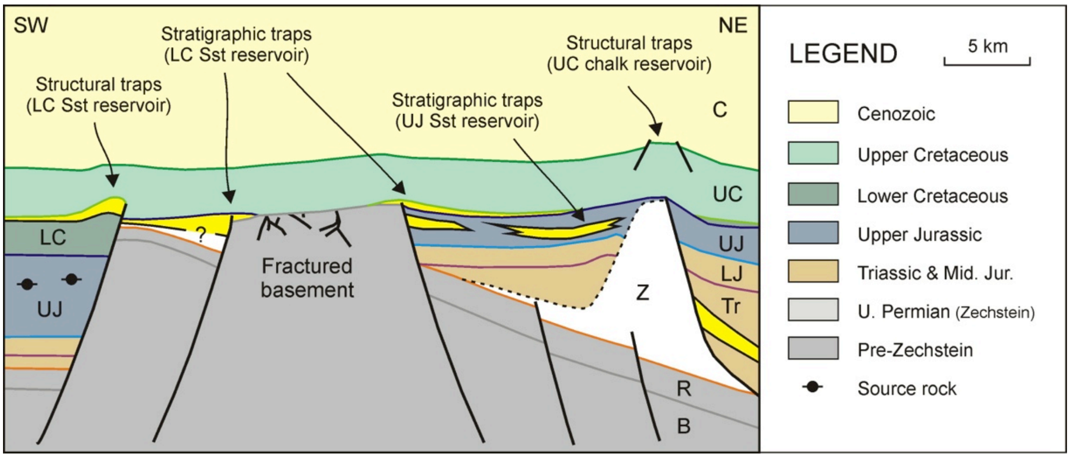
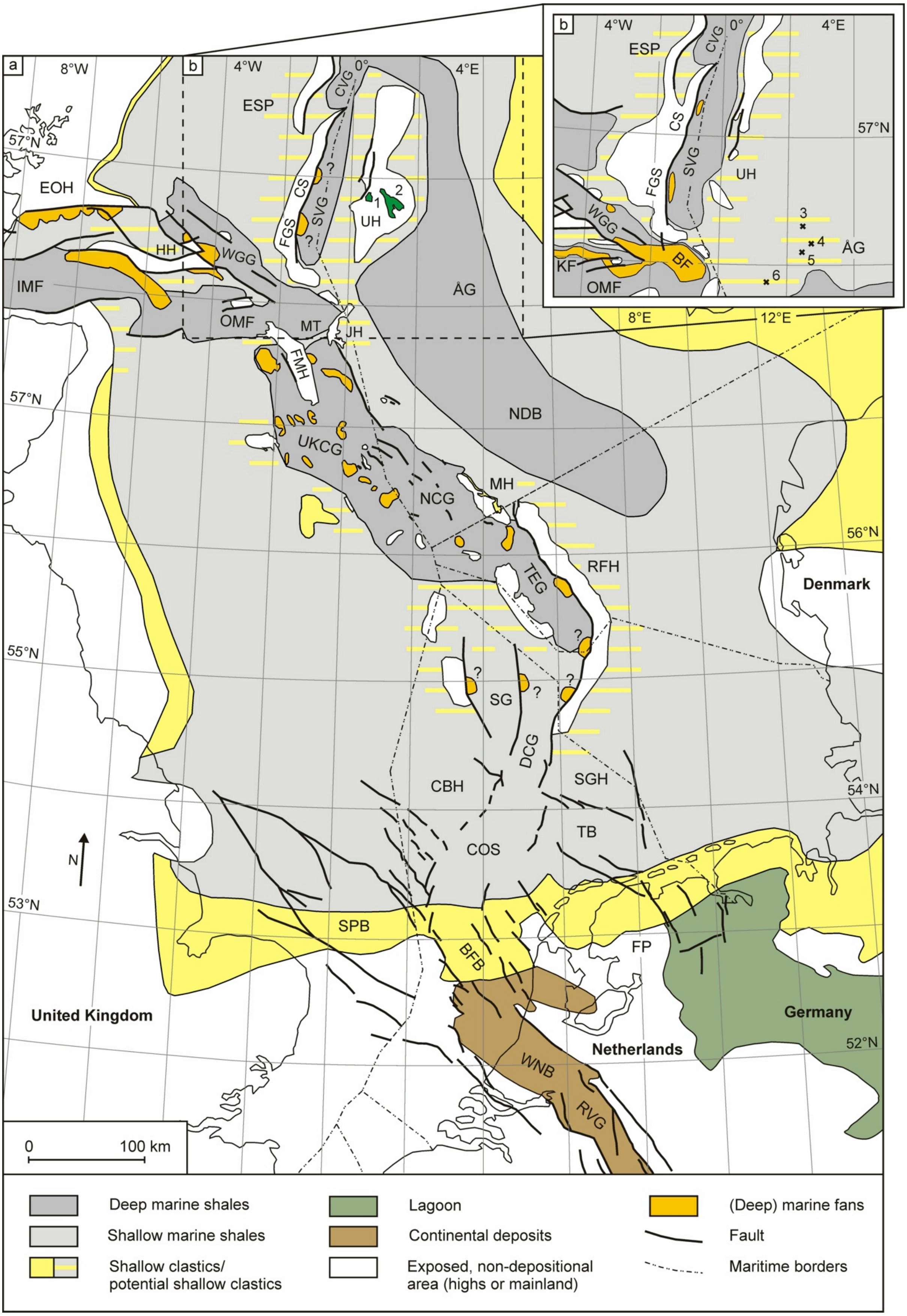


Fig. 10. Idealised cross section proposing the main potential reservoirs and traps in the Mandal High-Søgne Basin area. C: Cenozoic, UC: Upper Cretaceous, LC: Lower Cretaceous, UJ: Upper Jurassic. LJ: Lower Jurassic, Tr: Triassic, Z: Zechstein (evaporites), R: Rotliegend, B: Pre-Permian sediments and/or (metamorphic) Basement. Image modified after Rossland *et al*. (2013).



a
b
8°W
4°W
0°
4°E
8°E
12°E
57°N
56°N
55°N
54°N
53°N
52°N
EOH
HH
WGG
IMF
OMF
MT
JH
FMH
ESP
CVG
CS
SVG
FGS
UH
ÅG
NDB
UKCG
NCG
MH
TEG
RFH
SG
DCG
CBH
SGH
TB
COS
SPB
BFB
FP
WNB
RVG
KF
BF
N
0
100 km
United Kingdom
Netherlands
Germany
Denmark
Deep marine shales
Shallow marine shales
Shallow clastics/
potential shallow clastics
Lagoon
Continental deposits
Exposed, non-depositional
area (highs or mainland)
(Deep) marine fans
Fault
Maritime borders

Fig. 11. (a) Gross depositional environment overview of the Central and Southern North Sea in Ryazanian times (K10). (**b**) Gross depositional environment of the South Viking Graben area in Aptian times (K40-50), corresponding to the Aptian-Albian reservoir interval. Lower Cretaceous sand presence: (1) Edvard Grieg field, (2) Johan Sverdrup field, (3) well NO 7/10-1, (4) well NO 7/11/-1, (5) well NO 7/11-2, (6) well NO 7/3-1, ÅG: Åsta Graben, BF: Britannia Field, BFB: Broad Fourteens Basin, CBH: Cleaver Bank High, COS: Central Offshore Saddle, CS: Crawford Spur, CVG: Central Viking Graben, DCG: Dutch Central Graben, EOH: East Orkney High, ESP: East Shetland Platform, FP: Friesland Platform, HH: Halibut High, IMF: Inner Moray Firth, JH: Jæren High, FMH: Forties-Montrose High, KF: Kopervik Fairway, MH: Mandal High, MT: Marnock Terrace, NCG: Norwegian Central Graben, NDB: Norwegian-Danish Basin, OMF: Outer Moray Firth, RFH: Ringkøbing-Fyn High, RVG: Roer Valley Graben, SG: Step Graben, SGH: Schill Grund High, SPB: Sole Pit Basin, TB: Terschelling Basin, TEG: Tail End Graben (Danish Central Graben), UH: Utsira High, UKCG: UK Central Graben, WGG: Witch Ground Graben, WNB: West Netherlands Basin. Modified after Copestake *et al*. (2003), NPD (2017) for the South Viking Graben area, after Milton-Worsell *et al*. (2006), Copestake *et al*. (2003), Rossland *et al*. (2013) for the UKCG and NCG, after Vejbæk *et al*. (2010), after Pharaoh *et al*. (2010) for the Danish, German and (parts of) the Dutch Central Graben, and after Jeremiah *et al*. (2010) for the Southern North Sea.